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A MODEL FOR THE CALCULATION OF THE VOLUME FRACTION OF GLASS BINDER IN ABRASIVE CERAMIC TOOLS

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A model for the calculation of the volume fraction of glass binder in abrasive ceramic tools is proposed, assuming the glass interlayers between abrasive grains to be spherical particles and the grain shape is approximated by various bodies of revolution: spheres, cylinders, and two paraboloids joined along a circumference The use of the model makes it possible to estimate the minimum content of glass binder, with which no contact bridges are formed between the grains, and also the thickness of the glass interlayers between the grains.

Glass is commonly applied for binding corundum grains, cubic boron nitride, diamond, and other ultrahard materials in making abrasive tools (USSR Inventor's Certif. No. 1151442) [1]. The mass content of a binder in a material can be substantial: up to 90% (USSR Inventor's Certif. No. 338357). A binder is selected to satisfy the conditions of high strength and efficient performance of the tool with participation of a sufficiently large quantity of cutting edges of abrasive grains. This condition is presumably true even in the case where other known types of binders are used in the process (metallic, organic, or ceramic binders).

An efficient abrasive tool is a so-called restricted self-regulating system in which the working surface is self-sharpened with time as a consequence of worn grains being torn off the surface and new cutting edges becoming bared [2]. Otherwise the surface of the tool dulls and becomes greasy. Sometimes the operating efficiency can be increased by increasing the number of cutting edges of abrasive grains with a substantial decrease of the volume fraction of the binder. This is also considered as a positive aspect, since it decreases thermal stresses on the grain – binder interface caused by the difference in their expansion coefficients [3]. However, the bottom limit of the binder content is determined by the strength of material.

Let us assume that the structure of a material with a minimum possible volume fraction of glass binder X represents uniformly distributed abrasive grains separated by thin glass interlayers forming a continuous skeleton. There is no chemical interaction between the grains and the glass. A decrease in the amount of the glass binder below X will lead to the formation of contact bridges between the grains (i.e., will disturb the continuity of the vitreous skeleton phase) and a sharp decrease in the strength of material.

Let us accept the following calculation model for evaluation of X: the glass interlayers between abrasive grains consist of spherical particles with a radius r compactly packed in the form of a single layer on the grain surface (Fig. 1*a*). The abrasive grains in this model will be approximated by the following bodies of revolutions (Fig. 2): spheres with the radius R_1 (for the first calculation variant), cylinders with the height h and base radius R (for the second calculation variant), and by two paraboloids with equal heights H joined along a circumference with the radius R_0 (for the third calculation variant). The following condition of the equality of linear sizes is satisfied for the bodies of revolution selected: $h = 2R_1$, $R = R_0$, $H = R_1$.

In the accepted hexagonal packing of spherical particles of the vitreous phase each sphere and the vacancy between three adjacent spheres are projected on the surface of the body of revolution in the form of a circumference and a

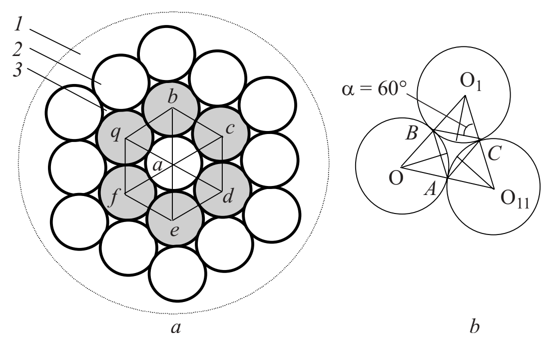

Fig. 1. Model for calculation of the volume fraction of glass binder: *a*) packing of a single layer of spherical glass particles on the surface of abrasive grains; *1*) surface of grains; *2*) glass spherical particle; each particle *a* is surrounded by six neighboring particles: *b*, *c*, *d*, *e*, *f*, and *q*; *3*) vacancy between spherical particles; *b*) geometric representation of contact between three spherical glass particles.

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curvilinear triangle, whose sides are formed by arcs *AB*, *BC*, and *AC* (Fig. 1*b*).

In the framework of geometrical concepts the surface area occupied by the three segments is $26.79 \times 10^{-2} r^2$ (I) and the surface area of the triangle *ABC* is $43.3 \times 10^{-2} r^2$ (II). The difference between expressions (II) and (I) is the surface area of the curvilinear triangle, which is equal to $16.51 \times 10^{-2} r^2$. The number of circumferences n is related to the number of curvilinear triangles m by the relationship $m = 2n$. Then one can write

$$S = \pi r^2 n + 16.51 \times 10^{-2} r^2 \times 2n,$$

whence

$$n = \frac{S}{3.47 r^2},$$

where S is the total surface area of the body of revolution.

The volume fraction of a single layer of spherical particles can be expressed as follows:

$$X = \frac{100}{(2V / vn) + 1},$$

where V is the volume of the body of revolution; v is the volume of the spherical glass particle equal to $\frac{4}{3}\pi r^3$.

In this case the value X for each calculation variant will be: the first calculation variant

$$X_1 = \frac{1.81 \times 10^2}{(R_1 / r) + 1.81} \quad \text{for} \quad V = \frac{4}{3}\pi R_1^3 \text{ and } S = 4\pi R_1^2; \tag{1}$$

the second calculation variant

$$X_2 = \frac{57.6\pi r(h + R)}{1.5Rh + 0.576\pi r(h + R)}$$
$$\text{for} \quad V = \pi R^2 h \text{ and } S = 2\pi R(h + R); \tag{2}$$

the third calculation variant

$$X_3 = \frac{100r[(4H^2 + R_0^2)^{3/2} - R_0^3]}{4.97R_0H^3 + r[(4H^2 + R_0^2)^{3/2} - R_0^3]}$$
$$\text{for} \quad V = \pi R_0^2 H \text{ and } S = \frac{\pi R_0}{3H^2}[(4H^2 + R_0^2)^{3/2} - R_0^3]. \tag{3}$$

To estimate the extent of reliability of the calculation model proposed (using each calculation variant), samples of Al_2O_3 (abrasive grain) – glass (binder) material were prepared. The initial material was electrocorundum powder of fraction 50 – 100 μm and glass powder of fraction 50 – 63 μm produced by milling window sheet glass. The powders were mixed in a preset ratio, and the powder mixture was poured into a mold and compacted by compression

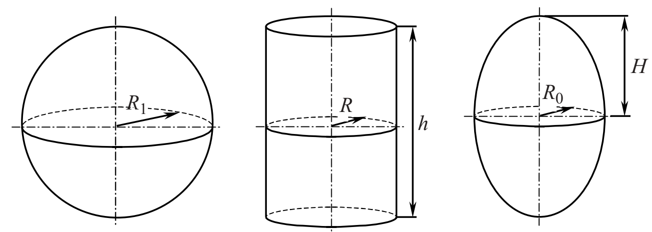

Fig. 2. Concept of abrasive grains as bodies of revolution.

at a pressure of 100 MPa. The resulting samples were sintered at 850°C for 1 h.

To estimate the volume fraction of glass powder in the mixture (X_1, X_2, X_3), the parameters r, R_1, h and R, H, R_0 have to be set. For this purpose glass and electrocorundum powders were analyzed using the optical spectroscopy method. Glass powder particles have a fragmentary shape with a prevalent linear size of 60 μm; accordingly, one can assume $r = 30$ μm for them. Electrocorundum glass particles have an elongated shape; for them the prevalent longitudinal size is 75 μm and the lateral size 40 μm. They can be approximated by spheres with $R_1 = 37.5$ μm, by cylinders with $R = 20$ μm and $h = 75$ μm, and by paraboloids joined along a circumference with $R_0 = 20$ μm and $H = 37.5$ μm. By substituting the specified values into formulas (1) – (3), the following values were calculated: $X_1 = 59.2$ (for $n_1 = 5.65$), $X_2 = 69.6$ (for $n_2 = 3.8$), and $X_3 = 72.5$ (for $n_3 = 2.19$). According to the model proposed, the estimated values $X_1 - X_3$ in a mixture of glass and electrocorundum powders have to ensure a distribution of spherical glass particles over the surface of abrasive grains in the form of a continuous single layer (it can be seen that this condition is satisfied with extremely low values of n, as the value r is comparable with the linear sizes of the bodies of revolution).

In our opinion, if the model proposed reliably reflects one of the calculation variants, the condition of continuity or the glass layer between the abrasive grains has to be satisfied also concerning the sintered material. The distribution of a vitreous phase between grains in a sintered material was analyzed using electron microscopy on surfaces of polished sections. With $X_1 = 59.2 \approx 60\%$ (the first calculation variant), contact bridges are registered between the grains (Fig. 3*a*), whereas with $X_2 = 69.6 \approx 70\%$ and $X_3 = 72.5 \approx 73\%$ (the second and the third calculation variants, respectively) continuous vitreous interlayers are always present between the grains (Fig. 3*b*). The latter fact is an indication of the higher reliability of the second and third calculation variants of the model compared with the first variant. This is presumably due to a closer correlation of the shape of the bodies of revolution with the real geometrical shape of abrasive grains in the specified calculation variants.

The materials obtained were tested for bending strength. The tests involved a three-point loading scheme for prismatic samples sized 8 × 8 × 50 mm at a deformation rate of

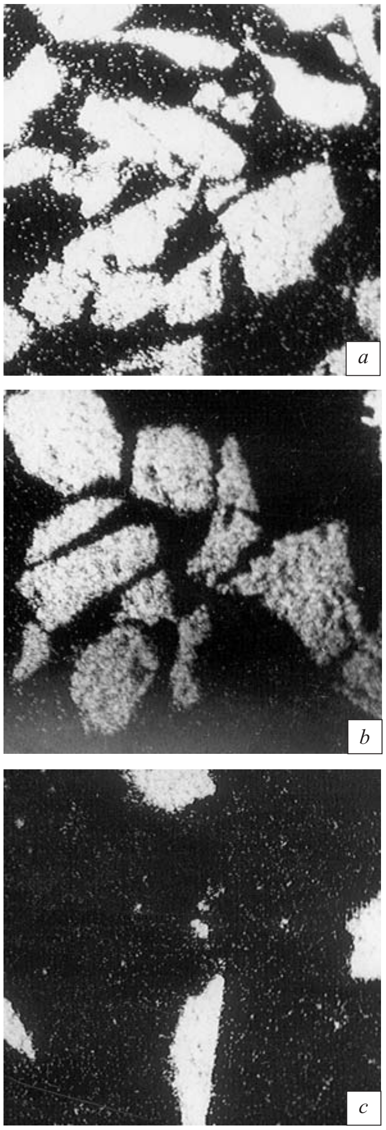

Fig. 3. Microstructure of Al_2O_3 (abrasive grain) – glass (binder) material in characteristic x-ray AlK_α radiation (× 300): *a*, *b*, and *c*) volume fractions of glass binder in material equal to 60, 70 – 73, and 90%, respectively; dark background) vitreous binder; light-colored inclusions) abrasive grains.

0.1 mm/min. In addition, samples with the volume fraction of the glass binder equal to 80 and 90% were tested as well. It was established that a clearly expressed strength maximum exists within an interval range of $X = 70 – 73\%$ (Fig. 4). Its manifestation is presumably due to the possibility of relaxation of stresses in thin glass interlayers between the abrasive grains. The decrease in strength for $X = 60\%$ is a consequence of a decrease in the carrying capacity of the sample section as a result of the formation of contact bridges between the grains. Its drop at $X = 80 – 90\%$ is accounted for by the role of the cutting edges of the grains as very effective stress concentrators distributed in a glass matrix (Fig. 3*c*).

It can be assumed that the value r in expressions (1) – (3) correlates with the half-thickness of the vitreous interlayer

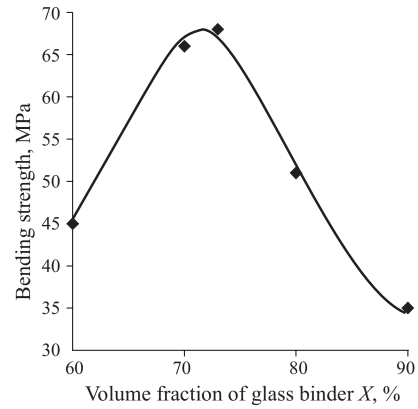

Fig. 4. Dependence of bending strength on volume fraction of glass binder.

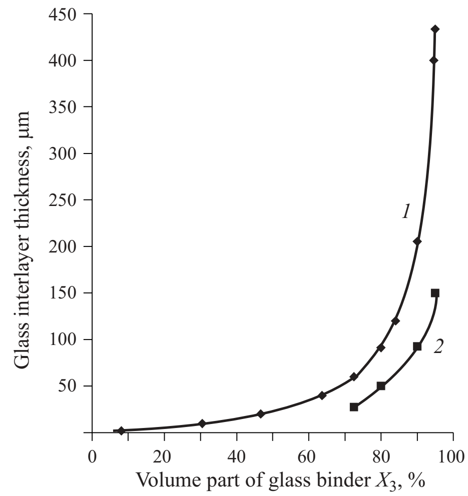

Fig. 5. Dependence of the thickness of glass interlayer ($\delta = 2r$) between abrasive grains on the volume fraction of glass binder.

$\delta/2$ between the abrasive grains, i.e., $\delta = 2r$. For the third calculation variant the dependence $\delta = f(X_3)$ is represented by curve *1* in Fig. 5. It is approximately described by a function of the form $y = 1.306e^{0.0568x}$. Curve *2* is constructed based on the average values of δ for sintered materials with a preset content of glass binder X_3. The average values of δ were calculated based on multiple measurements of the thickness of glass interlayers between various pairs of adjacent grains on the surface of a sample section. It can be seen that the value of δ measured at $X_3 = 70$, 80, and 90% is half as much as the values obtained in calculation, and at $X_3 = 95\%$ the measured value is one-third of the estimated one. This is due to molding pressure applied to the powder mixture and to the process of shrinkage in sintering. In the first case, the edges of glass particles are destroyed and, consequently, the vitreous interlayers become compressed, which decreases their thickness. In the second case we observe an approach of neighboring abrasive grains and a respective decrease in the glass inter-

layer thickness viscously flowing into the pores. The significant decrease in the value of δ (compared to an estimated value) at $X_3 = 95\%$ is presumably due to the higher degree of compaction of the powder mixture in molding, since the volume fraction of grains in this mixture drops to a 5%.

It should be noted that when the content of the vitreous binder in the experiments was below 70%, it was impossible to obtain continuous interlayers of glass binder between the abrasive grains. Possibly such continuity with a low content of glass can be achieved by using glass powder with particles of micron or submicron sizes and also by selecting a composition that would ensure improved wettability of the grain surface.

The calculation model proposed makes it possible to calculate the minimum volume fraction of a glass binder in an abrasive material, under which the vitreous phase forms a continuous skeleton and ensures absence of contact bridges between the grains. Furthermore, by setting characteristic sizes for abrasive grains and the volume fraction of the glass binder, this model makes it possible to estimate the thickness of the glass interlayers between the grains in the sintered materials. This is essential for the formation of abrasive tool structure, since the parameters estimated to a large extent determine its mechanical and service properties.

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